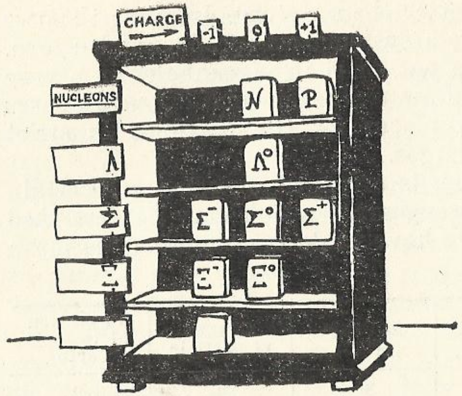


charge on each shelf. For nucleons—the oldest acquaintances of the baryon family—this mean charge of the multiplet is equal to $+1/2$. We shall use this value to compare the mean charges of all the other baryon multiplets (to obtain integral instead of fractional values, it is convenient to take the doubled difference of the mean charges of the multiplets). To illustrate, take the Ξ-particles. The mean charge is $-1/2$. The doubled difference between this and the nucleonic mean charge is -2. For a Σ-triplet we get (in the same way) the value -1, as for the Λ^0-particle. It is simple to perform similar calculations for mesons, taking pi-mesons as the standard (that is, taking their displacement as zero).

Do these figures bring anything to mind? Why, of course, they are the values of strangeness that played such an important role in the story about the weak interaction.

Interesting, indeed! Approaching the problem from another angle, that of particle systematics (we are not dealing with disintegrations or other mutual transformations), we again find it necessary to introduce strangeness.

Building blocks within building blocks

Confronted by the problem of putting our expanding collection of particles in order, we have chosen four features: spin, mass, charge and strangeness. The spin determines into which cabinet—baryon or meson—the particle is to be put (we do not consider leptons), the other quantities indicate the number of the shelf and its pigeonhole.

Now that everything is in order with complete systematics, of what use is it? Does it have any profound physical meaning? Have the characteristics been chosen properly to substantiate the classification? Imagine that instead of classifying particles we were dealing with biological systematics and took the weight of the animal as a basis. It might be that our closest relative would be a crocodile or a pig. It is not a question of whether this flatters us as human beings. Simply, systematics of that kind does not deepen our understanding of the animal kingdom.

In short, do we have a good classification of the elementary particles? Note first of all that all the characteristics are quantities that do not change under strong interactions. No matter what transformations occur due to the strong interaction, the electric charge of the original products is the same as that of the final products. The very same may be said of strangeness and spin. (Mass presents a more complicated problem, but we shall not deal with it here.)

The impression one gets from the foregoing is that there must be some kind of selection of material bearers of charge, strangeness, and spin, some kind of subparticles, which merge in specific combinations to form baryons and mesons and which do not appear or disappear in any transformations, but simply pass from one combination into another. If that is the situation, then conservation of charge or strangeness is no more remarkable than conservation of the number of parts in a child's erector set, irrespective of whether the parts go to make a locomotive or a windmill.

Elementary particles have long been poetically termed the building blocks of matter. But if there are subparticles, then these building blocks must consist of some other still more elementary building units. The idea is rather tempting, to say the least.

Quarks?

Firstly, let it be noted that our subparticles must have spin 1/2. Indeed, halves can be used to build integral

or half-integral spins, which is something we would not be able to do if we had at our disposal only building material with spin zero, unity or any other whole number.

But what about charge, mass and strangeness?

Here we are in for a surprise. The most harmonious picture is obtained, it appears, if we give up our habit of ascribing integral charges (that is, multiples of the electronic charge) to our building blocks within blocks, and use fractional charges.

Fractional charges! A short time ago this idea would have seemed preposterous. Yet three charges of this kind were introduced by Gell-Mann. He called them quarks.

How many quarks do we need? The fewer the better, naturally. The necessary minimum turns out to be three. In the literature, they are denoted by the letters p, n and λ (do not confuse with the symbols for the proton, neutron and lambda particle, which henceforth are designated by P, N and Λ).

As we have already agreed to do, the spins of all quarks will be taken as equal to 1/2, while the other properties can conveniently be set out in a table.

Symbol of quark	Electric charge	Strangeness	Baryon charge
p	+2/3	0	1/3
n	−1/3	0	1/3
λ	−1/3	−1	1/3

Now let us try to combine the quarks so as to obtain known particles. We can begin with the proton P. The proton has strangeness zero; hence, we confine ourselves to a set made up of p and n. A proton should consist of a total of three quarks, so that the total baryon number should come out to unity. If we further take into account that the charge of P is +1, we arrive at the only possible set: ppn. Incidentally, it is not the only one, for we forgot about spin. It is important that the total spin should equal 1/2. This can be achieved if we take it that the spins of two p-quarks are parallel and the spin of n is antiparallel to them (or to the z-axis, as physicists say, which means to some chosen direction in space). This

can be symbolized as follows:

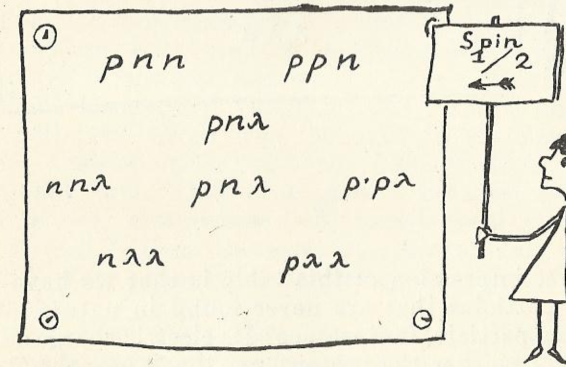
$$P = p\uparrow p\uparrow n\downarrow.$$

The arrows to the right of each symbol indicate the sense of its spin.

The recipe for forming particles out of quarks is now quite clear and does not appear to be complicated. Let us now try to arrange the quark triplets and see what we can get.

Let us first take combinations in which the spin is equal to 1/2. Which means that the spins of all quarks cannot have the same sense. A finer analysis based on the Pauli principle, which we discussed elsewhere in this book, indicates that not all spin combinations are allowed. For instance, if the total spin is 1/2, combinations of three identical quarks must be excluded. There are some other fine points that we shall not go into here. Let us simply write down the "permitted" combinations in rows. Inside each row, let the electric charge increase from left to right, and let the strangeness remain the same in each row; also let it diminish by unity when passing from one row to another one under it.

We then get the following table: *



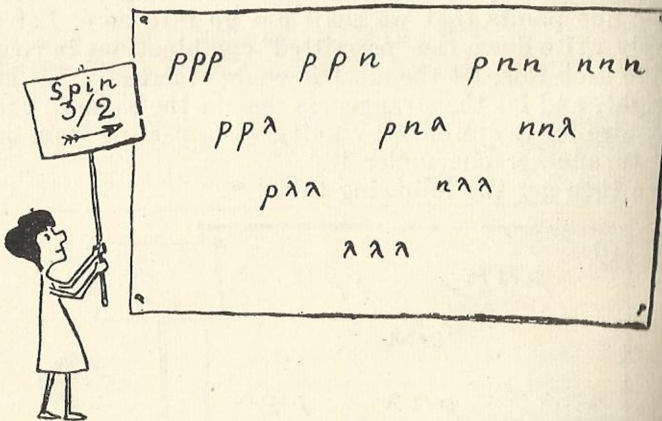
* The fact that we obtained two different combinations $pn\lambda$, was due to the possibility of different orientations of spin in this triplet. The Pauli principle does not allow two particles of the same kind to be in the same state at one time. But here all quarks are different, so the Pauli principle does not operate.

For the z-axis direction let us choose the direction of p. This will enable us to put an upward arrow for the first symbol of our triplet: $p\uparrow$. Now we must go through all combinations that yield total spin 1/2. There are obviously only two: $p\uparrow n\uparrow\lambda\downarrow$ and $p\uparrow n\downarrow\lambda\uparrow$. That explains why $pn\lambda$ appears twice in our table.

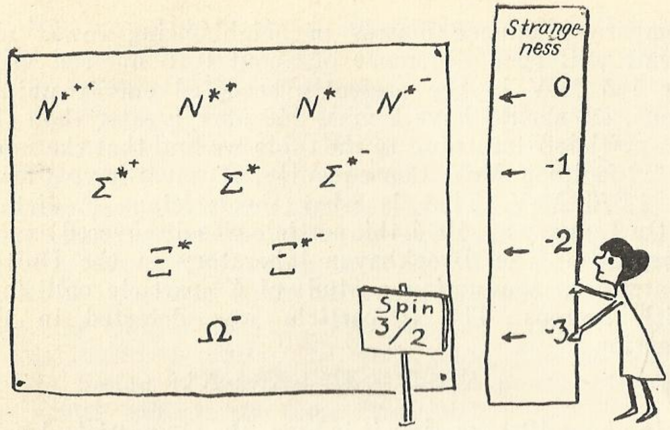
Now let us try to relate these triplets to particles. The combination *ppn* is the familiar proton. It is easy to see that *pnn* corresponds to the neutron. This means that the first row is a nucleon doublet. The charge singlet *pnλ* may be correlated with the Λ^0-particle; the third row yields the triplet $\Sigma^- \Sigma^0 \Sigma^+$ and, finally, the last row contains combinations of quarks which correspond exactly to the Ξ-doublet, as regards strangeness and electric charges.

The result is definitely good. We have already constructed what is known as a baryon octet.

Let's continue this exciting building game and try quark triplets with total spin 3/2. Observing the same hules as in the foregoing case, let us build another table.



The first impression of this table is that we have constructed particles that are never found in nature. What is that *ppp* particle, for instance? Its electric charge should be +2, yet neither the proton, nor the Σ, nor the Ξ-particle has charge greater than unity. And the resonances? We have forgotten the resonances, yet they too must be brought into the general scheme of our classification. Among the resonances is the particle we need—the first of the resonance family: N^{*++}. Now we have a place for it in our systematics. Places will be found for the other resonances as well. Let's start out with the following table:



A predicted meeting

This is a rather familiar table. The asterisks show that we are dealing with resonances which are the excited states of particles with the corresponding symbols: the plus and minus signs indicate electric charge. But there is something new here too, the symbol Ω^-. A little over a year ago it was not mentioned in the most detailed surveys of elementary particles. Only a few enthusiastic theoreticians—those who believed in the new systematics—insisted on the existence of this particle. "Look for it," they said. They even gave a detailed description: charge —1, strangeness —3, baryon number +1, spin equal to 3/2. Even the mass was theoretically predicted. How? Very simply (everything is simple in afterthought).

A glance at the table of resonances will show us that the masses increase downwards from row to row. At the same time, one λ-quark is added as we go downwards from one row to the next. Lambda is absent in the top row, there is one λ in the next, two in the next one down, and, finally, Ω^- consists of three λ-quarks. If we correlate the growth in mass with the growth in number of quarks, we will find that *p*- and *n*-quarks (to which we ascribe identical masses) are lighter than the λ-quark. We can even estimate how much lighter. All we have to do is

compare resonance masses in neighbouring rows. The result will be a difference of about 0.16 nucleon mass (or 146 MeV in the presently accepted energy units). Thus, Ω^- should have a mass 146 MeV greater than the Ξ^*-particle. Returning to the table we find that the mass of Ξ^* is 1,530 MeV. Consequently, Ω^- must have a mass of 1,676 MeV. That is what theoreticians predicted.

On January 31, 1964, this particle was discovered experimentally! The Brookhaven laboratory in the United States was conducting a study of K^--particle collisions with protons. The Ω^--particle was detected in the reaction

$$K^- + P \longrightarrow \Omega^- + K^+ + K^0.$$

In about 10^{-8} sec after it is born, the Ω^--particle decays as follows: $\Omega^- \longrightarrow \Xi^0 + \pi^-$. The relatively long lifetime is due to the fact that decay according to strong patterns (that is, due to strong interactions) is prohibited by the conservation of strangeness; as we have already pointed out, change in strangeness is possible only in disintegrations due to the weak interaction.

The discovery of the Ω^--particle and the amazing precision with which theoretical predictions were corroborated could not but create a very strong impression. If systematics had earlier been regarded as an elegant, ingenious, but not very convincing playground for the imagination, feelings among physicists changed radically when the Ω^--particle was discovered. Big events were in the offing.

Advances galore

The new classification brought one success after another. Mesons and boson resonances fitted into the general system very naturally and easily. Bosons are particles with integral spin. Which means that they may be built up out of an even number of quarks. To be more precise, out of an even number of quarks and antiquarks*, for we want to get particles with a baryon charge of zero.

* Antiquarks are denoted by the quark symbols with a bar on top.

(In the case of antiquarks, the baryon charge, like the other quantum numbers, is opposite in sign to the charge of the corresponding quarks.)

The simplest combinaitons of this kind have the forms: $\bar{p}p$, $n\bar{n}$, $\lambda\bar{\lambda}$, $p\bar{n}$, $\bar{p}\lambda$, etc. If the spins are antiparallel, the resulting particles have zero spin. For example, the positive pion should be regarded as a combination $p\downarrow\bar{n}\downarrow$. True enough, the charge comes out to $2/3 + 1/3 = 1$, and the strangeness is zero, as it should be for a positive pion. If you want to build a strange meson, say K^+, take the combination $p\bar{\lambda}$. The electric charge of such a combination is unity, the strangeness, plus unity. To obtain bosons of integral spin, choose quark-antiquark pairs with spins in the same direction.

Don't bother writing it all out. We are sure the reader will believe us when we say that mesons and boson resonances fit into the framework of this systematics just as neatly as baryons.

And that is not all that the theory has achieved. Assuming that quarks have magnetic moments proportional to their charges, we can find a relationship between the magnetic moments of the particles made up of these quarks; for instance, we can find the ratio of the magnetic moments of the proton and neutron. It comes out to 3/2, while experiment yields 1.46. Brilliant agreement.

Difficulties arise

Just when the quarks were resolving problems and confidence in these new particles was growing, we would have to come up against some more difficulties. Such startling success, even triumph, such a brilliant prediction of a new particle, even if one prefers to disregard the systematization of known particles, and such an elegant explanation of the properties of these particles, such as the relationships between their magnetic moments—and then suddenly "difficulties".

What kind and where?

When Gell-Mann was asked whether quarks existed (their introduction into science was largely his doing), he said "Who knows?"

True, we don't know as yet. Which is much like the situation with the vector boson—the carrier of the weak interaction—about which we know almost everything,

except whether it actually exists or not. Perhaps the rational kernel that is so evident in particle systematics should not have been interpreted so quickly in the spirit of pictorial models of building blocks within blocks.

Quark adherents seek confirmation of their views even in historical parallels. For one thing, they point to the molecular theory that was formulated before direct proof was obtained of the existence of molecules. Then one could say that phenomena occur "as if molecules existed". But today we know that they do exist.

True, this parallel could be countered with other no less instructive cases. Maxwell constructed electrodynamics on the basis of a light-carrying ether, but we know today that there is no such ether. Fourier derived the presently used equations of heat conduction in the belief that heat was conveyed by some sort of ubiquitous fluid, yet caloric is never mentioned any more, except perhaps by historians.

Historical parallels are tricky things.

But why resort to such mebulous and unconvincing arguments instead of simply examining experiments? Couldn't we try to detect quarks experimentally? All the more so since these particles should, due to their fractional charge, be stable in the free state and prominent on the background of other particles. The search for quarks has begun. However, it would seem easier to create them in collisions brought about in particle accelerators. Simple indeed! If all particles consist of quarks, take any particle and bombard it with a suitable projectile and quark fragments should spatter in all directions.

The idea is simple, but the execution isn't. Our atom-smashing machines are not powderful enough. But nature has the accelerators we need. Once in a while cosmic-ray particles plunge into the earth's atmosphere with truly cosmic velocities. If such super-powerful particles collided with atomic nuclei present in the atmosphere, we should obtain some free quarks. We have already suggested that free quarks should be stable particles and after being born should behave something like this: quarks surrounded by "ordinary" particles attracted to them (these particles, incidentally, cannot completely neutralize them electrically since they have integral charges) form relatively large "blobs", which drop to the surface

of the earth or land in the ocean. This is important. If they hit a water surface, they should sink to the bottom and form fairly large concentrations of quarks. Then all one would have to do is scoop up this bottom water and evaporate it to get a sort of quark sludge.

No experiments of this kind have been performed. What is more, we are not sure that it is so easy to tell the quarks how to behave. Do we really know that much about these hypothetical particles? So far we have built quark models of familiar elementary particles more or less in the way a child builds with blocks. But the child's structure is stationary, while quarks are constantly on the move. The systems we are attempting to construct must be dynamic because—if for no other reason—the general principles of quantum mechanics prohibit particles closed in a small volume from being stationary. Quarks are in constant motion. We did not try to include their movements in our classification, but attempts are being made to do something in this respect and some advances have been registered, though the general situation with regard to quark motions is still very hazy.

Problems of the internal dynamics of quarks are closely tied in with yet another fundamental problem, that of the forces which maintain quark systems. That interquark interactions exist goes without saying. We even know that the interaction energy is very great. Otherwise, a relatively slight blow would knock any particle into its constituent quarks. The quark interaction energies must be colossal, hence also the mass defect. If in atomic nuclei the mass defect amounts to a fraction of one per cent of the total mass, then in particles made up of quarks it is close to one hundred per cent. The mass of quarks is presently considered to be from 7 to 10 times that of the nucleon mass. The proton consists of three quarks, and their total mass is of the order of twenty to thirty nucleon masses. How can it be that parts weighing 30 units form a whole that weighs one unit? We know now. When a whole forms, energy equivalent to 29 mass units is released. The binding energy is the same. This is a fantastic energy, far beyond anything we know at present.

But what forces cement quarks together that way? What is the nature of interquark interactions? And are

BARYON RESONANCES*

State	Mass, MeV	Resonance width, MeV	J^P	I, S	Decay types (and their relative weights)
P	938.256 ± 0.005		$1/2^+$		
n	939.550 ± 0.005				
$\underline{N^*_{1/2}}$	~ 1480	~ 240	$1/2^+$		πN
$N^*_{1/2}$	1518 ± 10	$\left\{ \begin{matrix} 56 \\ 125 \end{matrix} \right.?$	$3/2^-$		$\left\{ \begin{matrix} \pi N : \pi\pi N : \pi N^*_{3/2}\ (1335) \\ \sim 80\% : \ ? \ : ? \end{matrix} \right.$
$N^*_{1/2}$	1688	100	$5/2^+$	1/2.0	$\left\{ \begin{matrix} \pi N : \pi\pi N : K\Lambda : \pi N^*_{3/2}\ (1236) \\ \sim 80\% : \ ? \ : ? : ? \end{matrix} \right.$
$N^*_{1/2}$	2190	~ 200	?		$\left\{ \begin{matrix} \pi N \\ \sim 30\% \end{matrix} \right.$
$\underline{N^*_{1/2}}$	2645 ± 10	230	?		πN
$\underline{N^*_{1/2}}$	2700	~ 100	?		$\eta N : \pi N$ $\sim 6\%$
$N^*_{3/2}$	1236 ± 2	125	$3/2^+$		πN
$N^*_{3/2}$	1924	170	$\underline{7/2^+}$		$\pi N : \Sigma K : \pi N^*_{3/2}$ (1236)
$N^*_{3/2}$	2360	~ 200	?	3/2.0	πN
$\underline{N^*_{3/2}}$	2520		?		πN
$\underline{N^*_{3/2}}$	2825	260	?		πN
$\underline{N^*_{5/2}}$	1560 ± 20	220 ± 20	?	5/2.0	$p\pi^+\pi^+$
Λ	1115.40 ± 0.11		$1/2^+$		
Y^*_0	1405	50	?		$\left\{ \begin{matrix} \Sigma\pi : \Lambda\pi\pi \\ 100 : (<1) \end{matrix} \right.$
Y^*_0	1518.9 ± 1.5	16 ± 2	$3/2^-$	0, −1	$\left\{ \begin{matrix} \Sigma\pi : \bar{K}N : \Lambda\pi\pi \\ (55 \pm 7) : (29 \pm 4) : (16 \pm 2) \end{matrix} \right.$
$\underline{Y^*_0}$	1660		$1/2$		$\Lambda\eta$
Y^*_0	1815	70	$\underline{5/2\pm}$		$\left\{ \begin{matrix} \bar{K}N : \Sigma\pi : \Lambda\pi\pi : \Lambda\eta \\ \underline{80 : (<10) : (<15)} : ? \end{matrix} \right.$
Σ^+	1189.41 ± 0.14				
Σ^0	1192.4 ± 0.3		$1/2^+$		
Σ^-	1197.08 ± 0.19				
Y^*_1	1382.1 ± 0.9	53 ± 2	$3/2+$	1, −1	$\left\{ \begin{matrix} \Lambda\pi : \Sigma\pi \\ (96 \pm 4) : (4 \pm 4) \end{matrix} \right.$
Y^*_1	1660 ± 10	44 ± 5	$\underline{3/2^-}$		$\left\{ \begin{matrix} \bar{K}N : \Sigma\pi : \Lambda\pi : \Lambda\pi\pi : \Lambda\pi\pi \\ 5 : 31 : 21 : 27 : 16 \end{matrix} \right.$
$\underline{Y^*_1}$	1765 ± 10	60 ± 10	$5/2^-$	1, −1	$\left\{ \begin{matrix} \bar{K}N: \\ 60\% \end{matrix} \right.$
Ξ^0	1314.3 ± 1.0		$1/2^+$		
Ξ^-	1320.8 ± 0.2		$5/2^-$		
Ξ^*	1529.1 ± 1.0	7.5 ± 1.7	$3/2\pm$	12, −2	$\left\{ \begin{matrix} \Xi\pi \\ \sim 100\% \end{matrix} \right.$
$\underline{\Xi^*}$	1810 ± 20	~ 70	?		$\left\{ \begin{matrix} \Xi^*\pi : \Xi\pi\pi : \Xi\pi : \Lambda\bar{K} : \Sigma\bar{K} \\ 45 : (>10) : 9 : 35 : 1.5 \\ (<50) : (<50) : (10)\ 100 : ? \end{matrix} \right.$
Ω^-	1675 ± 3		?	0, −3	

* Question marks and the symbol ⎵ indicate "unreliable"; J is spin, P-parity; I-isotopic spin, and S-strangeness.

these interactions of one kind? Finally, in what relation do they stand to already known forces? For instance, do not nuclear forces, which we have interpreted as a manifestation of meson exchange by nucleons, reduce to some kind of special types of interaction between quarks, all the more so since nucleons consist of quarks and mesons (according to our model) are quark-antiquark pairs.

These and many-other questions confront us. Put briefly, we must investigate the dynamical basis of the new particle systematics.

There is much that we still have to learn. For one thing, we cannot answer the question posed at the very start of the book: How many fundamental types of interaction are there, after all (a short time back we were sure there were only four).

We are positive that our grasp of nature has become more profound. These new ideas and the new classification of elementary particles, for one, (even if we disregard the remarkable discoveries described here) are of lasting value if for no other reason than they boldly pose specific questions and map out definite pathways. And even if tomorrow it is proved experimentally that there are no quarks at all in nature, this will not cross out the advances made in systematics, but will simply indicate that our models were only rough approximations to the great original—NATURE.

TO THE READER

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